NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT No. 561

EFFECT OF NOZZLE DESIGN ON FUEL SPRAY AND FLAME FORMATION IN A HIGH-SPEED COMPRESSION-IGNITION ENGINE

By A. M. ROTHROCK and C. D. WALDRON

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft. (or mi.)
Time	t	second	s	second (or hour)	sec. (or hr.)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb.
Power	P	horsepower (metric)		horsepower	hp.
Speed	V	kilometers per hour	k.p.h.	miles per hour	m.p.h.
		meters per second	m.p.s.	feet per second	f.p.s.

2. GENERAL SYMBOLS

W, Weight $= mg$

g, Standard acceleration of gravity $= 9.80665$ m/s² or 32.1740 ft./sec.²

m, Mass $= \frac{W}{g}$

I, Moment of inertia $= mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ, Coefficient of viscosity

ν, Kinematic viscosity

ρ, Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C. and 760 mm; or 0.002378 lb.-ft.$^{-4}$-sec.^{2}

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb./cu.ft.

3. AERODYNAMIC SYMBOLS

S, Area

S_w, Area of wing

G, Gap

b, Span

c, Chord

$\frac{b^2}{S}$, Aspect ratio

V, True air speed

q, Dynamic pressure $= \frac{1}{2}\rho V^2$

L, Lift, absolute coefficient $C_L = \frac{L}{qS}$

D, Drag, absolute coefficient $C_D = \frac{D}{qS}$

D_o, Profile drag, absolute coefficient $C_{D_o} = \frac{D_o}{qS}$

D_i, Induced drag, absolute coefficient $C_{D_i} = \frac{D_i}{qS}$

D_p, Parasite drag, absolute coefficient $C_{D_p} = \frac{D_p}{qS}$

C, Cross-wind force, absolute coefficient $C_C = \frac{C}{qS}$

R, Resultant force

i_w, Angle of setting of wings (relative to thrust line)

i_t, Angle of stabilizer setting (relative to thrust line)

Q, Resultant moment

Ω, Resultant angular velocity

$\rho\frac{Vl}{\mu}$, Reynolds Number, where l is a linear dimension (e.g., for a model airfoil 3 in. chord, 100 m.p.h. normal pressure at 15° C., the corresponding number is 234,000; or for a model of 10 cm chord, 40 m.p.s. the corresponding number is 274,000)

C_p, Center-of-pressure coefficient (ratio of distance of *c.p.* from leading edge to chord length)

α, Angle of attack

ϵ, Angle of downwash

α_o, Angle of attack, infinite aspect ratio

α_i, Angle of attack, induced

α_a, Angle of attack, absolute (measured from zero-lift position)

γ, Flight-path angle

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EFFECT OF NOZZLE DESIGN ON FUEL SPRAY AND FLAME FORMATION IN A HIGH-SPEED COMPRESSION-IGNITION ENGINE

By A. M. Rothrock and C. D. Waldron

SUMMARY

Fuel was injected from different types of injection nozzles into the combustion chamber of the N. A. C. A. combustion apparatus, operated as a compression-ignition engine; high-speed motion pictures were taken at the rate of 2,200 frames per second of the fuel sprays and the combustion. Single-orifice nozzles of 0.008-, 0.020-, and 0.040-inch diameter, and multiorifice nozzles having 2, 6, and 16 orifices were tested. Nozzles having impinging jets and slit orifices were also included. The photographs indicate that the rate of vapor diffusion from the spray is comparatively slow and that this slow rate of diffusion for combustion chambers with little or no air flow prevents the compression-ignition engine, with the present methods of fuel injection, from giving the high performance inherent in the high compression ratios. The sprays from multiorifice nozzles destroyed the air movement to a greater extent than did those from single-orifice nozzles. It is concluded that high performance cannot be realized until the methods of distributing the fuel are improved by means of the injection-nozzle design, air flow, or both.

INTRODUCTION

In the high-speed compression-ignition engine the most difficult problem to solve is that of obtaining an intimate mixture of the fuel and the air so that the fuel may be burned both completely and efficiently. As yet no method has been devised to obtain a mixture that will completely utilize both the air and the fuel in the combustion chamber. Compression-ignition engines are therefore operated with an excess of air in order to obtain the low fuel consumption inherent in the high compression ratios.

Methods of mixing the fuel and air correctly are based on bringing the fuel to the air, on bringing the air to the fuel, or on both. During the past few years the N. A. C. A. has been conducting an extensive investigation of the effects of nozzle design on the general characteristics of fuel sprays for compression-ignition engines to learn to what extent the injection nozzle can be utilized in bringing the fuel to the air in the combustion chamber. Engine tests have been reported in references 1 and 2, experiments on the distribution in the fuel sprays in references 3, 4, and 5, and experiments on fuel-spray disintegration in reference 6. In a more recent series of tests, the results of which will be later published, Lee has determined qualitatively the comparative distribution of the fuel from nozzles identical with or similar to those described in reference 5.

When the distribution of the fuel in the liquid stage has been determined, the next step is to determine the additional distribution caused by the diffusion of the fuel vapors. In order to make this determination it is necessary to conduct tests with the engine or with some special apparatus that reproduces very closely the engine conditions. Such tests, reported herein, have been conducted with the N. A. C. A. combustion apparatus (reference 7). By means of this apparatus high-speed motion pictures were taken of the fuel spray and flame formation in a single-cylinder test engine operating under load as a compression-ignition engine for a single cycle. These tests, in addition to forming a part of the general research on injection-nozzle design, also form a part of the general research on combustion being conducted by the Committee (references 8 and 9).

APPARATUS AND METHODS

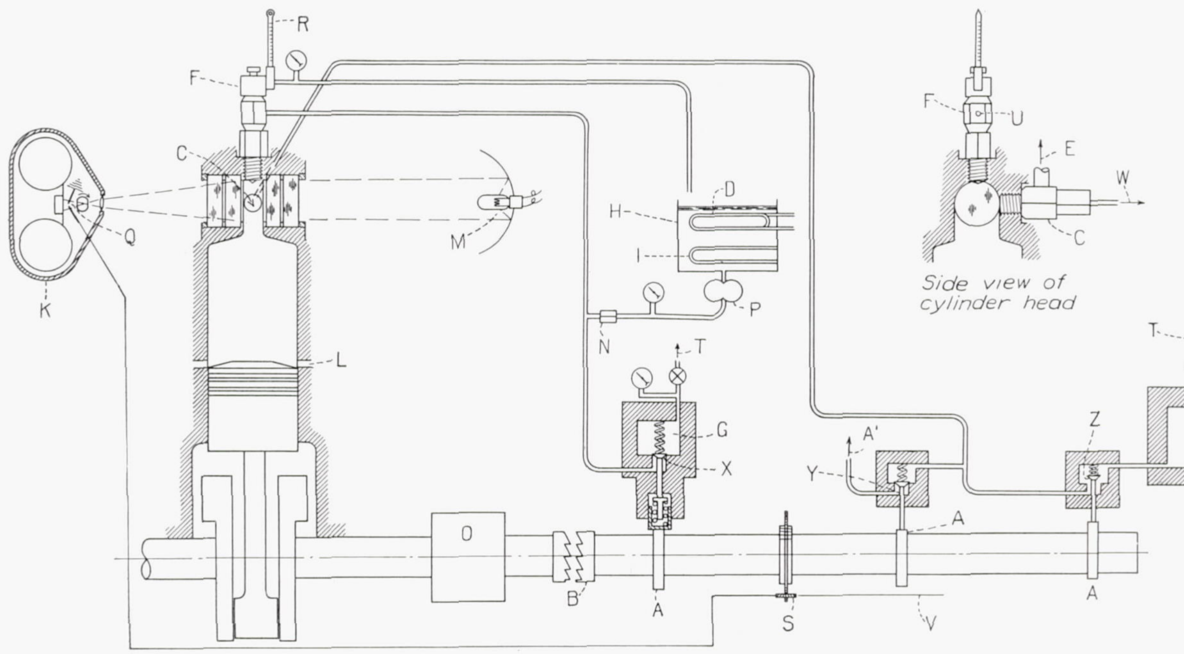
The N. A. C. A. combustion apparatus (fig. 1) in its present form has been described in reference 9. The single-cylinder test engine is brought to speed by an electric motor. When the desired conditions are reached, a clutch is engaged and a camshaft makes a single revolution at one-half engine speed. This revolution of the camshaft causes a single charge of fuel to be injected into the combustion chamber of the engine. The compression-release valve is open for all engine revolutions except the one during which the injection of the fuel takes place. The following conditions were maintained constant during the tests:

Engine bore	inches	5
Engine stroke	do	7
Height of inlet ports	do	0.5
Engine speed	revolutions per minute	1,500

Compression ratio (based on 6.5-inch stroke)—
With windows in both sides 13.2
With indicator in one side 13.9
Engine-coolant temperature outgoing .... ° F .. 150
Air-fuel ratio (see table I) 17
Start of injection .... crankshaft degrees B. T. C .. 15

The different nozzles tested are shown in figure 2. Data on the atomization, penetration, and general appearance of the sprays from these or similar nozzles have been given in references 3, 4, and 5. The injection-valve opening pressure was adjusted to maintain as nearly as possible a constant injection pressure for all nozzles at the desired air-fuel ratio of approximately 17. In some cases the injection pressure varied appreciably from the mean. (See table I.) Although both the injection-valve opening pressure and the injection pressure varied, previous results obtained by the Committee (references 3 to 6) have shown that these variations do not affect the validity of the results.

The diesel fuel used in these tests was the same as that described in reference 9. For each of these tests the fuel-injection system was calibrated to determine the injection pressure necessary to obtain the desired fuel quantity. The injection valve was put into the engine and two indicator cards were taken. The indicator was removed, the glass windows were inserted in both sides of the cylinder head, and two series of motion pictures of the spray and combustion flame were taken. The indicator was again installed and two more indicator cards were taken as a check. Finally, the injection valve was removed and the fuel quantity again weighed. Because the injection valve was disassembled so frequently, it was impossible to hold the fuel quantity within the close limits maintained in the tests of air-fuel ratio reported in reference 9. Table I lists the various fuel quantities together with the actual deviation in weights and the estimated air-fuel ratios:



A, cam.
B, clutch.
C, compression-release valve.
D, cooling coil.
E, exhaust.
F, fuel-injection valve.
G, fuel reservoir.
H, fuel tank.
I, heating coil.
J, high-pressure reservoir.
K, high-speed camera.
L, inlet-air ports.
M, lamp and reflector.
N, 0.020-inch orifice.
O, phase-changing gears, 2:1 reduction.
P, primary pump.
Q, spark gap.
R, thermometer.
S, timing-spark switch.
T, to hand pump.
U, to injection pump.
V, to spark coil.
W, to valve Z.
X, valve.
Y, valve.
Z, valve.
A′, waste.

FIGURE 1.—Diagrammatic sketch of the N. A. C. A. combustion apparatus.

TABLE I

NOZZLE AND FUEL-INJECTION DATA

Nozzle	Fuel weight (Pounds)	Limits (Pound)	Injection pressure (lb./sq. in.)	Estimated air-fuel ratio [1]	Total discharge-orifice area (sq. in.)
Single 0.008-inch	2.99×10^{-4}	$\pm0.15\times10^{-4}$	4,200	16.9	0.50×10^{-4}
Single 0.020-inch	2.87	±.37	5,950	17.6	3.14
Single 0.040-inch	2.97	±.18	3,900	17.0	12.56
2-orifice	2.93	±.20	6,000	17.2	9.83
6-orifice	2.95	±.10	6,000	17.1	9.73
16-orifice	2.95	±.31	5,000	17.1	20.57
Slit-orifice	2.95	±.22	5,750	17.1	4.40
Multiorifice-slit	2.97	±.18	5,500	17.0	----
2-impinging-jets	3.02	±.15	5,500	16.7	19.25
4-impinging-jets	3.02	±.26	5,250	16.7	28.28

[1] See reference 9.

The indicator cards obtained in these tests were not sufficiently accurate to determine either the brake mean effective pressure developed during the power cycle or to obtain the specific fuel consumption. For this reason

the nozzles were also tested in the N. A. C. A. single-cylinder test engine using the combustion chamber described in reference 2. This combustion chamber is similar to that used in the N. A. C. A. combustion apparatus for the present tests. Nozzle K–4, described in reference 2, instead of the 6-orifice nozzle shown in figure 2, was used in the engine tests because of the differences in the combustion-chamber shapes.

RESULTS AND DISCUSSION

A composite of all the spray and flame photographs is shown as figure 3.[1] The rate at which the motion pictures were taken varied from 2,100 to 2,400 frames a second; hence, the timing sparks at 90 crankshaft degrees after top center are not in line. The time scale represents an average of all the runs.

Composites of the indicator cards obtained on the combustion apparatus with the different fuel-injection nozzles are shown as figure 4. The indicator cards show vibrations of the indicator diagram caused by the rate of pressure rise in the combustion chamber. These vibrations are not sufficiently intense to prohibit the use of the cards as an indication of the course of the combustion.

The analysis of the data presented in the report is chiefly based on the spray and flame photographs; consideration is also given to the data that were obtained with the test engine and are presented in table II. In table II the data are presented for the conditions of constant maximum cylinder pressure and of constant injection advance angle. Under either operating condition, the 6-orifice nozzle gave the best performance, and the 2-orifice nozzle the next best. The single 0.008-inch orifice was not tested on the engine because of its extremely long injection period. The other nozzles followed in fairly close order with some variation depending on whether the maximum cylinder pressure or the injection advance angle was kept constant.

TABLE II

ENGINE-PERFORMANCE TEST DATA

Nozzle	Constant maximum cylinder pressure, 800 pounds per square inch			Constant injection advance angle, 12 crankshaft degrees B. T. C.			
	B. m. e. p. (lb./sq. in.)	B. f. c. (lb./hp. hr.)	Air-fuel ratio	B. m. e. p. (lb./sq. in.)	B. f. c. (lb./hp. hr.)	Air-fuel ratio	Max. cyl. press. (lb./sq. in.)
Single 0.020-inch	84.8	0.654	17.0	66.0	0.823	17.3	545
Single 0.040-inch	79.0	.692	17.2	71.0	.790	16.8	690
2-orifice	91.3	.590	17.4	89.0	.628	16.8	745
6-orifice	115.0	.472	17.2	115.0	.472	17.2	800
16-orifice	90.0	.618	17.0	77.4	.720	16.9	650
Slit-orifice	85.8	.618	17.7	75.3	.716	17.4	645
Multiorifice-slit	87.7	.620	17.1	77.5	.716	16.9	675
2-impinging-jets	83.4	.690	16.2	62.0	.898	16.8	550
4-impinging-jets	83.4	.640	17.5	70.0	.784	17.1	585

[1] These results have also been prepared as a technical motion picture film (400 ft. 16 mm.) entitled "Effects of Nozzle Design on Combustion in a Compression-Ignition Engine," by A. M. Rothrock, E. C. Buckley, and C. D. Waldron, *Technical Film No. 6, N. A. C. A., 1935. This film may be obtained on loan* from the Committee.

A comparison of the indicator cards shown in figure 4 indicates that the 6-orifice nozzle and the multi-orifice-slit nozzle gave the best performance and that the 2-orifice nozzle was next. In a comparison of

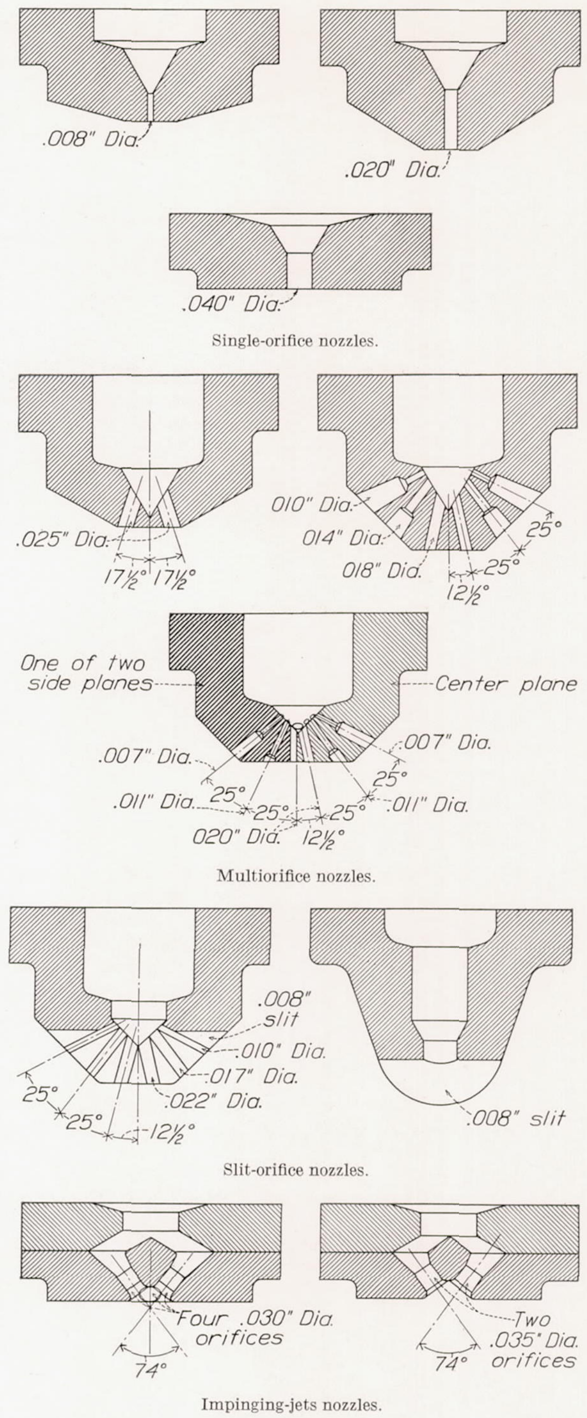


FIGURE 2.—Nozzles tested.

these results with those given in table II, allowance must be made for the differences in the combustion chambers and also in the air flow in the chambers.

In a previous report (reference 8) the form of combustion chamber used in these tests has been termed a

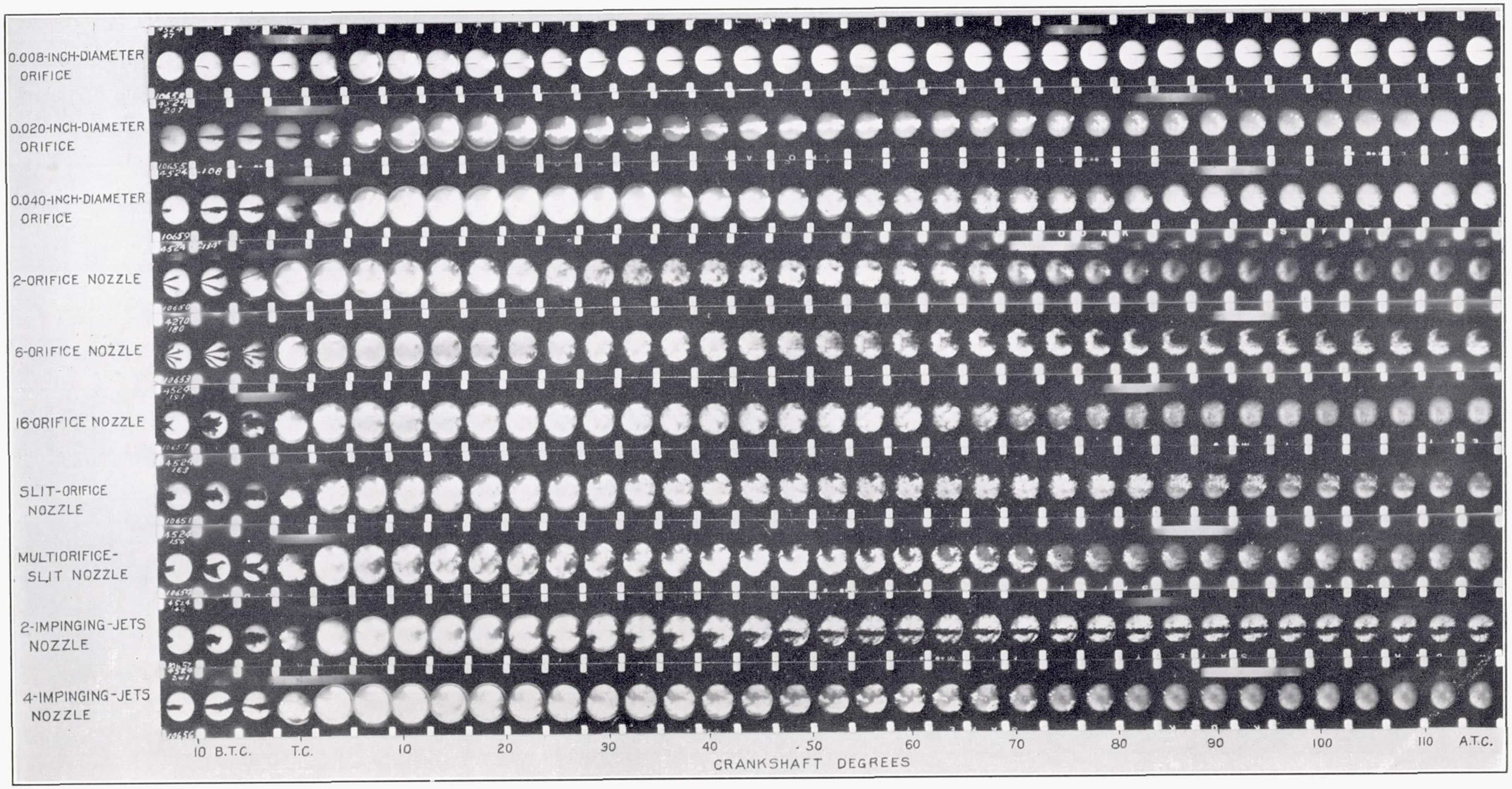


FIGURE 3.—Effect of nozzle design on fuel spray and flame formation. Air-fuel ratio, 17; compression ratio, 13.2; speed, 1,500 r. p. m.; jacket temperature, 150° F.

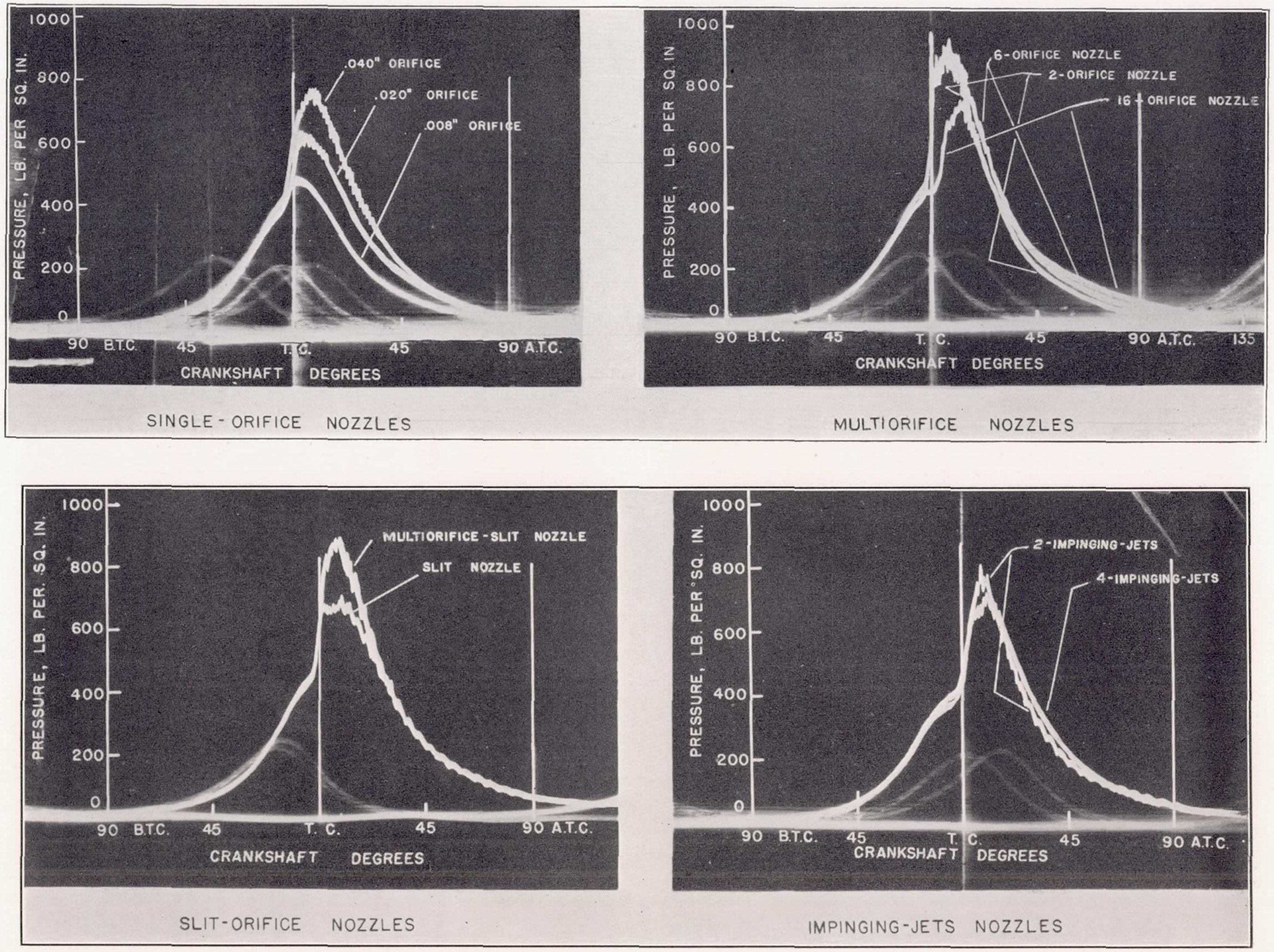


FIGURE 4.—Indicator cards obtained with different nozzles.

"quiescent" chamber. Subsequent tests (reference 9) have shown that air flow does exist in the combustion chamber, probably induced as the air enters the engine cylinder through the intake ports. Tests, the results of which are at present unpublished, show that this air movement consists of a vortex in the combustion chamber. A schlieren photograph of this vortex in the combustion chamber is shown in figure 5. The vortex appeared most intense in the left-hand side of the chamber and successive frames of the motion picture showed that it rotated in a counterclockwise direction and moved in the plane of the combustion chamber. As shown in figure 3 of reference 8, the inducted air entered the cylinder at a high pressure difference resulting in a high initial velocity. For this reason the air flow is comparable with that obtained in a highly supercharged engine.

Because the vortex itself, as well as the air within the vortex, is in motion, the fuel sprays may be bent first in one direction and then another. These spray movements are more visible in the enlargements of the fuel-spray development and of the first part of the burning, shown in figures 6 to 9. Since the purpose of this report is to discuss the effects of the nozzle design and not of the air movement, the effects of the air movement will be treated only incidentally.

Single-orifice nozzles (figs. 3, 4, and 6).—The most important fact to be learned from the photographs of the sprays and flame from the single-orifice nozzles is that the rate of vapor diffusion from the fuel spray is comparatively slow although it can be assisted to some extent by the nozzle design. With the single 0.008-inch orifice, the injection of the fuel lasted from 15° before top center to about 180° after top center. Such an injection period is, of course, entirely impracticable from considerations of engine operation, but it was used in the present series of tests to obtain additional information on spray diffusion. The spray traverses the combustion chamber comparatively slowly. The fuel that does vaporize and form a combustible mixture is carried from the spray to the lower left-hand quarter of the combustion chamber, the flame being first photographed at about 4° after top center. The indicator card shows that the pressure rise caused by the combustion started at about 2° before top center. Figure 3 shows no flame at top center. The difference in the start of combustion is within the accuracy of the results. The flame then surrounds the spray in the portion of the chamber away from the nozzle and spreads more or less symmetrically to both sides. In the successive frames the visible portion of the flame grows smaller as the flame is apparently drawn down into the displacement volume of the engine. Beyond 30° after top center the flame is no longer visible although the fuel continues to be sprayed from the injection nozzle. In no case did the flame reach the top of the chamber at the injection nozzle. With the 0.008-inch orifice nozzle the actual discharge pressure at the orifice was probably considered in excess of the 4,200 pounds per square inch in the injection reservoir (reference 10). The high velocity and the small orifice both tended to lessen the mean drop diameter of the atomized fuel (reference 4). The fineness of the atomization in turn assisted the vaporization. Because of the slow mass rate of fuel discharge, however, the actual rate of vapor formation was probably low. This low rate of vaporization accompanied by the low rate of vapor diffusion (reference 9) resulted not only in a low rate of burning but also in limiting the flame to a small portion of the combustion chamber.

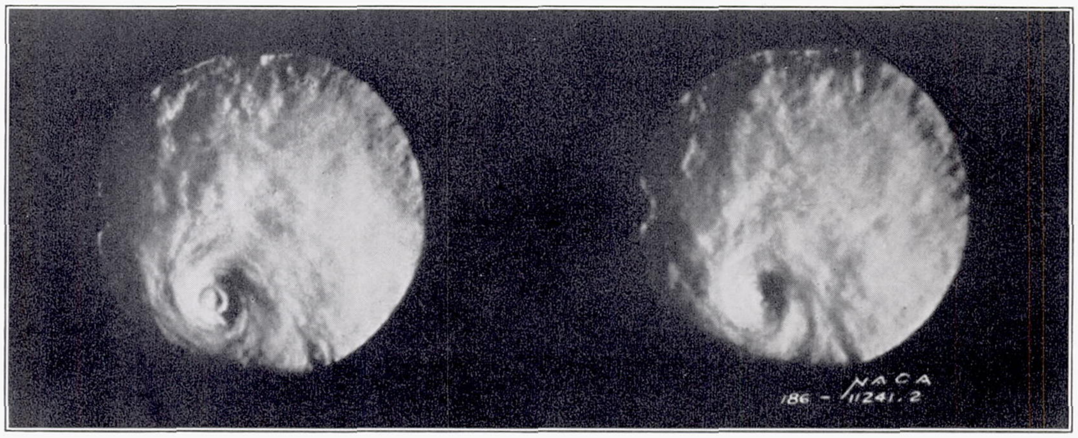


FIGURE 5.—Schlieren photograph of the air vortex in the combustion chamber. The air in the vortex is apparently rotating in a counterclockwise direction, and the vortex itself is rotating around the chamber in a counterclockwise direction.

Holfelder (reference 11), using an apparatus somewhat similar to that described in the present report, has shown that when the combustion air is quiescent the burning starts close to the core of the fuel spray from a single-orifice nozzle and does not travel far from the volume included in the spray envelope.

When the orifice diameter was increased to 0.020 inch, the linear rate of fuel discharge was decreased (reference 10) but the mass rate and also the mean drop diameter (reference 4) were increased. The increased

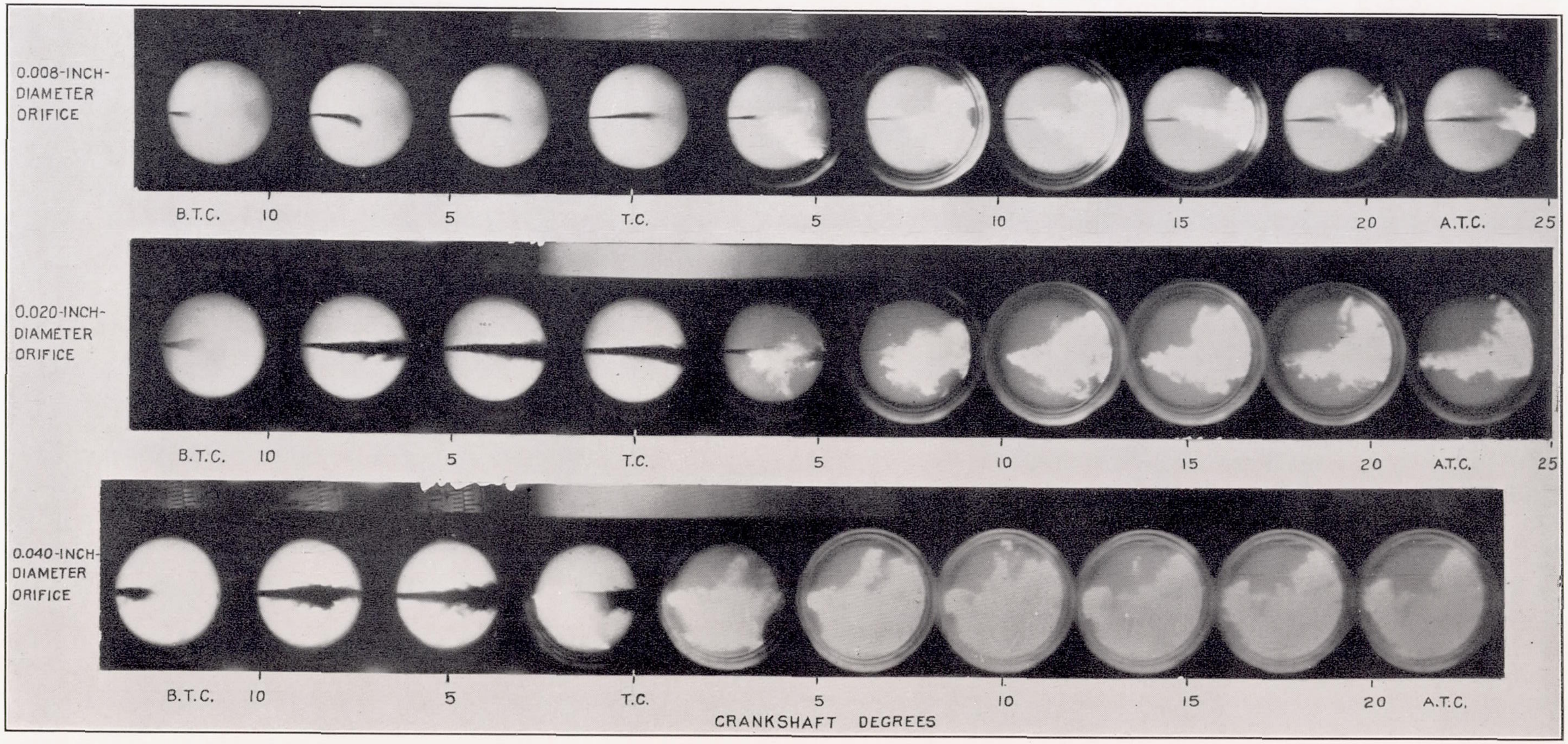


FIGURE 6.—Fuel spray and flame formation with single-orifice nozzles. Air-fuel ratio, 17; compression ratio, 13.2; speed, 1,500 r. p. m.; jacket temperature, 150° F.

mass rate of discharge more than compensated for the decreased atomization so that the rate of formation of a combustible mixture and its diffusion were increased. Consequently the flame spread to a greater area than it did with the smaller orifice. As the piston proceeded on its downward stroke, the flame did not disappear from view as it did when the 0.008-inch orifice nozzle was used but tended to remain in the visible portion of the combustion chamber. The photographs show clearly that the incandescent gases can remain in the combustion chamber without diffusing through the unburned portion of the gases. The results emphasize the slow rate of diffusion of the gases in the combustion chamber.

When the discharge-orifice diameter was increased to 0.040 inch, the area covered by the flame was still further increased although it did not fill the visible portion of the combustion chamber. The flame first appeared in the upper left-hand portion of the chamber. The comparison of the three series of photographs shows that, as the orifice diameter was increased, the first appearance of flame traveled from the bottom of the combustion chamber toward the top, always remaining on the leeward side of the spray. Examination of check runs made under the same or similar conditions showed that this tendency was definite. It is probable that, as the orifice diameter was increased, the velocity at the nozzle decreased and consequently the moving air was more able to deflect the spray envelope from its original path, thus forming a combustible mixture in the upper part of the chamber.

The indicator cards and the flame photographs both show that the ignition lag decreased as the orifice diameter was increased. This decrease is apparently caused by the earlier formation of a combustible mixture. The indicator cards show a large change in pressures as the orifice diameter is increased from 0.008 to 0.020 inch and a smaller change as the diameter is further increased to 0.040 inch. The cards also indicate that with the 0.040-inch orifice the amount of combustible mixture formed is the greatest, although the rate of pressure rise indicates that the rate of formation of the mixture is about the same as with the 0.020-inch orifice.

Multiorifice nozzles.—The results obtained with the multiorifice nozzles are shown in figures 3, 4, and 7. In each case the combustion reached a higher maximum pressure than with the single-orifice nozzles and was apparently more efficient. With the 2-orifice nozzle the flame covered a slightly greater area than with the single 0.040-inch orifice and the flame did not reach the upper portion of the chamber except close to the nozzle. When the number of orifices was increased to six, nearly all the combustion chamber was reached by flame; the air flow had no apparent effect on the spread of the flame other than at the start. The fuel distribution was improved over that obtained with the single- or 2-orifice nozzles since it had to traverse only half the distance between each of the six sprays.

The results with the 16-orifice nozzle were disappointing as regards the resulting combustion. When so many orifices were provided, it was necessary to have a large over-all discharge area, 2.11 times that of the 6-orifice nozzle. The injection pressure was therefore still further decreased so that a point was reached at which the penetration was also decreased (reference 12) and the proportional distribution between the orifices was destroyed. Had the over-all area of the discharge nozzles been maintained constant, the penetration with the 16-orifice nozzle would still have been decreased because of the smallness of the orifices.

The first appearance of flame with the multiorifice nozzles was close to the fuel sprays, indicating that the multiorifice nozzles had an appreciable effect in destroying the air movement in the combustion chamber.

The indicator cards for the multiorifice nozzles show that the 6-orifice nozzle gave the highest maximum cylinder pressure. The expansion line for the 16-orifice nozzle crosses that for the 6-orifice nozzle. This pressure difference is, however, within the precision of the cards. The spread and duration of the flame with the 6-orifice nozzle indicate, as do the data of table II, that the maximum engine output was obtained with the 6-orifice nozzle. The results presented in figure 7 show why in many cases a nozzle that gives a spray which appears to be particularly good from design considerations may turn out to be inferior. When the over-all area of the nozzle becomes too great for the injection system as a whole, the spray penetration is decreased to such an extent that the decrease in the fuel dispersion results in a decrease in engine performance. The limitations of the injection pump may be such that the nozzle design most advantageous to the combustion chamber cannot be used.

High-distribution nozzles (Figs. 3, 4, 8, and 9).—Nozzles giving uniformly distributed fuel sprays have been the subject of numerous tests. Most compression-ignition engines, however, employ either a multiorifice nozzle or a pintle nozzle. Although high-distribution nozzles present particularly interesting characteristics, they have not, in general, given satisfactory engine performance. The results shown in the photographs indicate that the trouble has been caused by an incorrect combination of combustion-chamber design, air flow, and nozzle design.

The slit nozzle shows distribution characteristics that are particularly interesting. The spray penetration is low so that probably this nozzle can be used beneficially only with air flow. When the slit is com-

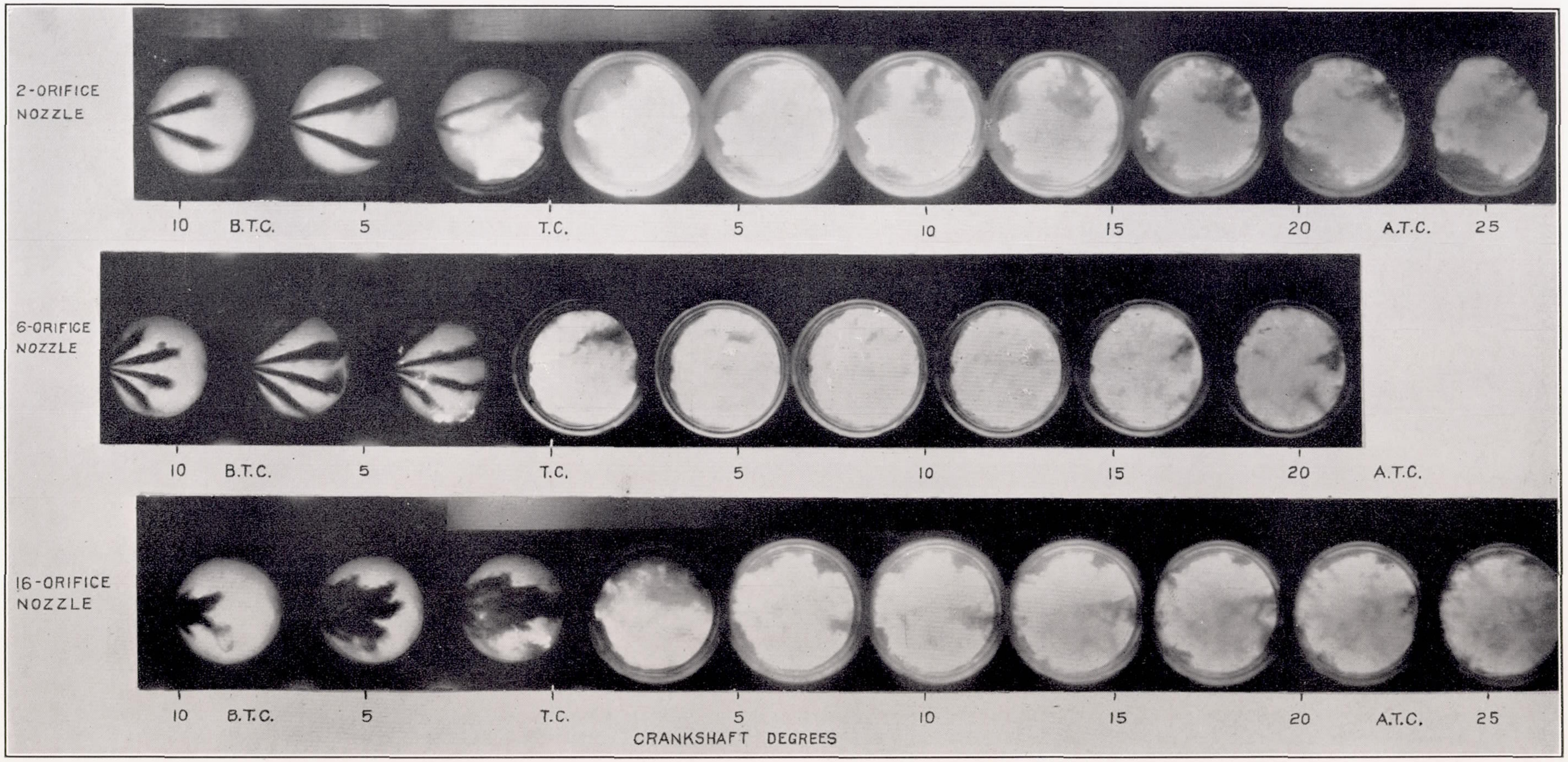


FIGURE 7.—Fuel spray and flame formation with multiorifice nozzles. Air-fuel ratio, 17; compression ratio, 13.2; speed, 1,500 r. p. m.; jacket temperature, 150° F.

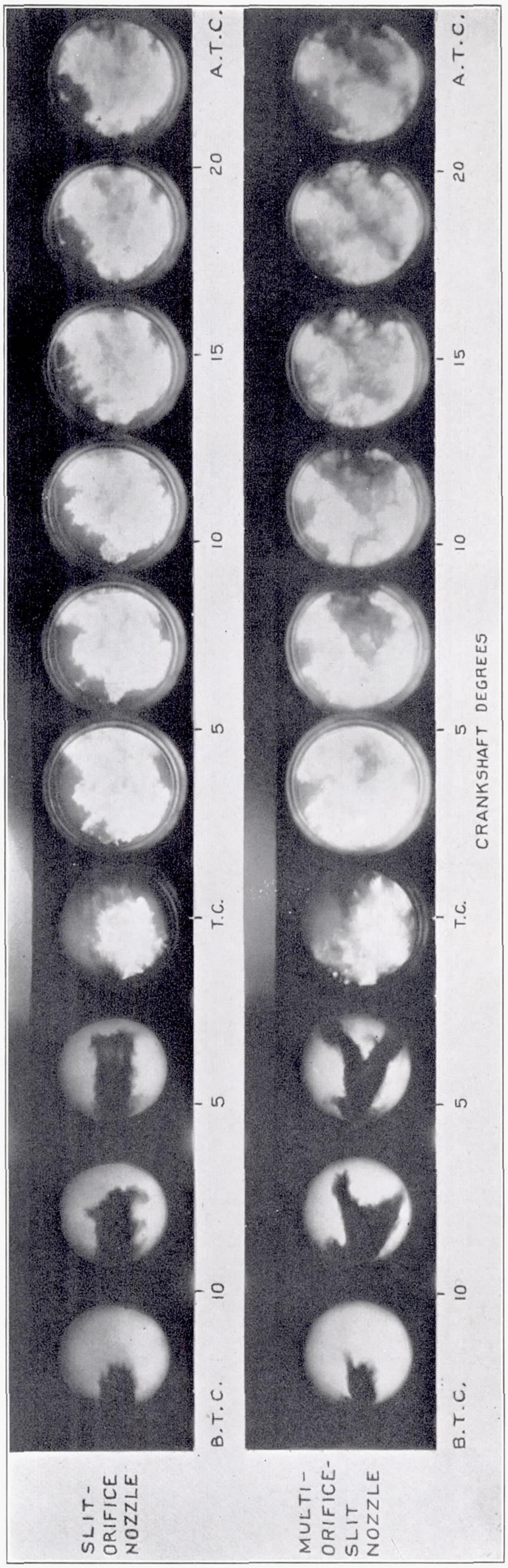


FIGURE 8.—Fuel spray and flame formation with slit-orifice and multiorifice-slit nozzles. Air-fuel ratio, 17; compression ratio, 13.2; speed, 1,500 r. p. m.; jacket temperature, 150° F.

bined with the multiorifice nozzle, the flow through the nozzle may be considerably different from that of either nozzle used separately. The photographs in figure 8 show that the slit gave an apparently symmetrical spray; the combination of the slit and multiorifice destroyed this symmetry. In neither case did the flame fill the combustion chamber, showing that, although the distribution within the spray may have been uniform, the fuel was too localized, resulting in an overrich mixture in the spray.

The 2-impinging-jets nozzle showed results somewhat similar to the slit nozzle. The 4-impinging-jets nozzle showed a spray of low penetrating ability, compared with a single-orifice nozzle, but one in which the core was of larger diameter and therefore of lower density. The indicator cards show that the rate of burning with this nozzle was comparatively slow, indicating a slow rate of diffusion of the fuel vapors into the unused air. For best results the low spray penetration must be assisted by air flow. The photographs show that the spray was more affected by the air movement in the chamber than was the case with the single-orifice nozzles.

In the construction of a high dispersion nozzle it is sometimes difficult to obtain a symmetrical spray. It can often be obtained only by trial and error, in which case considerable time can be saved by injecting the spray against some substance such as modeling clay (reference 3) in order to study the spray symmetry.

Comparison of all the nozzles.—By the comparison of all the nozzles, it is apparent that the distribution of the fuel relative to the combustion chamber can be regulated to a large extent by the design of the fuel-injection nozzle. This conclusion is not new in itself, but the extent to which the flame spread can be controlled by nozzle design, however, has not been known heretofore, and by the flame spread the diffusion of the fuel vapors is indicated. The results emphasize the fact that the rate of diffusion of the fuel vapor as well as of the fuel spray is a comparatively slow process and must be assisted by some other means if the combustion with little or no excess air is to be efficient. The indicator cards show that in some cases the difference in cylinder pressures is not so much as flame photographs might indicate, showing that the extent of flame spread is not the only criterion of the extent of combustion. From this fact it must be concluded that the extent of combustion within the flame area and also the rate must vary considerably. The tests emphasize again, as was brought out in reference 9, that in the high-speed compression-ignition engine the maximum performance of the engines is at present limited by the rate of diffusion of the fuel vapors and that, if the power and the economy are to be those inherent in the high compression ratio of the compression-ignition engine, the diffusion of the fuel by the injection nozzle and the air flow must be improved.

The results for all the nozzles show that in a nearly quiescent combustion chamber the best distribution of the fuel spray is obtained with a nozzle containing several plain round orifices. These results are in accordance with those already reported in references 1 and 2. In this type of chamber, good penetration of the fuel, which is very important, is best obtained by dense sprays from single round-hole orifices. It is possible that with extremely high injection pressures, e. g., in excess of 15,000 pounds a square inch, the high-dispersion nozzle might prove superior to the multiorifice nozzle.

CONCLUSIONS

The following conclusions are presented:

1. The rate of diffusion of the fuel vapors is too slow to provide satisfactory mixing of the fuel with the air in the combustion chamber.

2. The rate of fuel-spray distribution and the rate of fuel-vapor diffusion with respect to the combustion chamber and not the rate or fineness of fuel atomization, the rate of fuel vaporization, nor the rate of fuel injection are the chief obstacles to be overcome in the development of the high-speed compression-ignition engine.

3. The high performance inherent in the high compression ratio of the compression-ignition engine cannot be realized until a better method of distributing the fuel is obtained by improving the injection nozzle design, by the use of air flow, or by both.

4. Fuel sprays from a multiorifice nozzle destroy the air movement in a combustion chamber to a greater extent than do the sprays from single-orifice or high-dispersion nozzles.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *March 19, 1936.*

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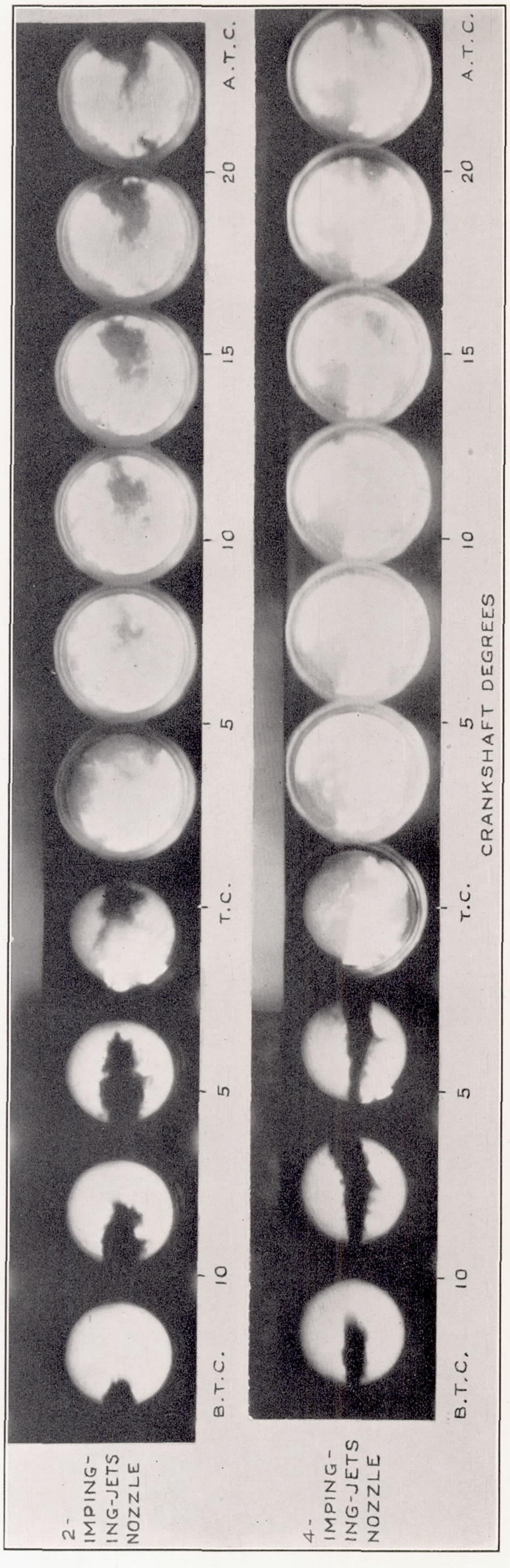

FIGURE 9.—Fuel spray and flame formation with impinging-jets nozzles. Air-fuel ratio, 17; compression ratio, 13.2; speed, 1,500 r. p. m.; jacket temperature, 150° F.

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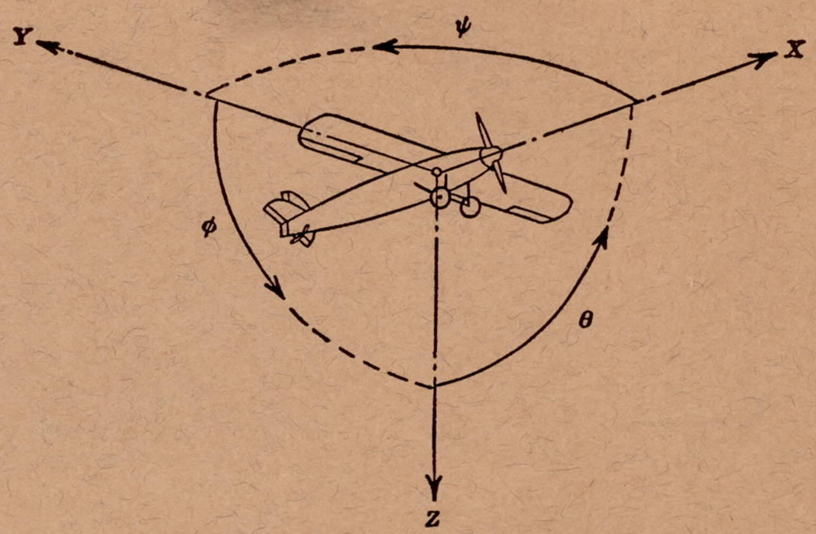

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l = \frac{L}{qbS}$ (rolling) $C_m = \frac{M}{qcS}$ (pitching) $C_n = \frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D, Diameter
p, Geometric pitch
p/D, Pitch ratio
V', Inflow velocity
V_s, Slipstream velocity
T, Thrust, absolute coefficient $C_T = \frac{T}{\rho n^2 D^4}$
Q, Torque, absolute coefficient $C_Q = \frac{Q}{\rho n^2 D^5}$

P, Power, absolute coefficient $C_P = \frac{P}{\rho n^3 D^5}$
C_s, Speed-power coefficient $= \sqrt[5]{\frac{\rho V^5}{P n^2}}$
η, Efficiency
n, Revolutions per second, r.p.s.
Φ, Effective helix angle $= \tan^{-1}\left(\frac{V}{2\pi r n}\right)$

5. NUMERICAL RELATIONS

1 hp. = 76.04 kg-m/s = 550 ft-lb./sec.
1 metric horsepower = 1.0132 hp.
1 m.p.h. = 0.4470 m.p.s.
1 m.p.s. = 2.2369 m.p.h.

1 lb. = 0.4536 kg.
1 kg = 2.2046 lb.
1 mi. = 1,609.35 m = 5,280 ft.
1 m = 3.2808 ft.